

EUV and Novel Patterning Materials Progress and Challenges

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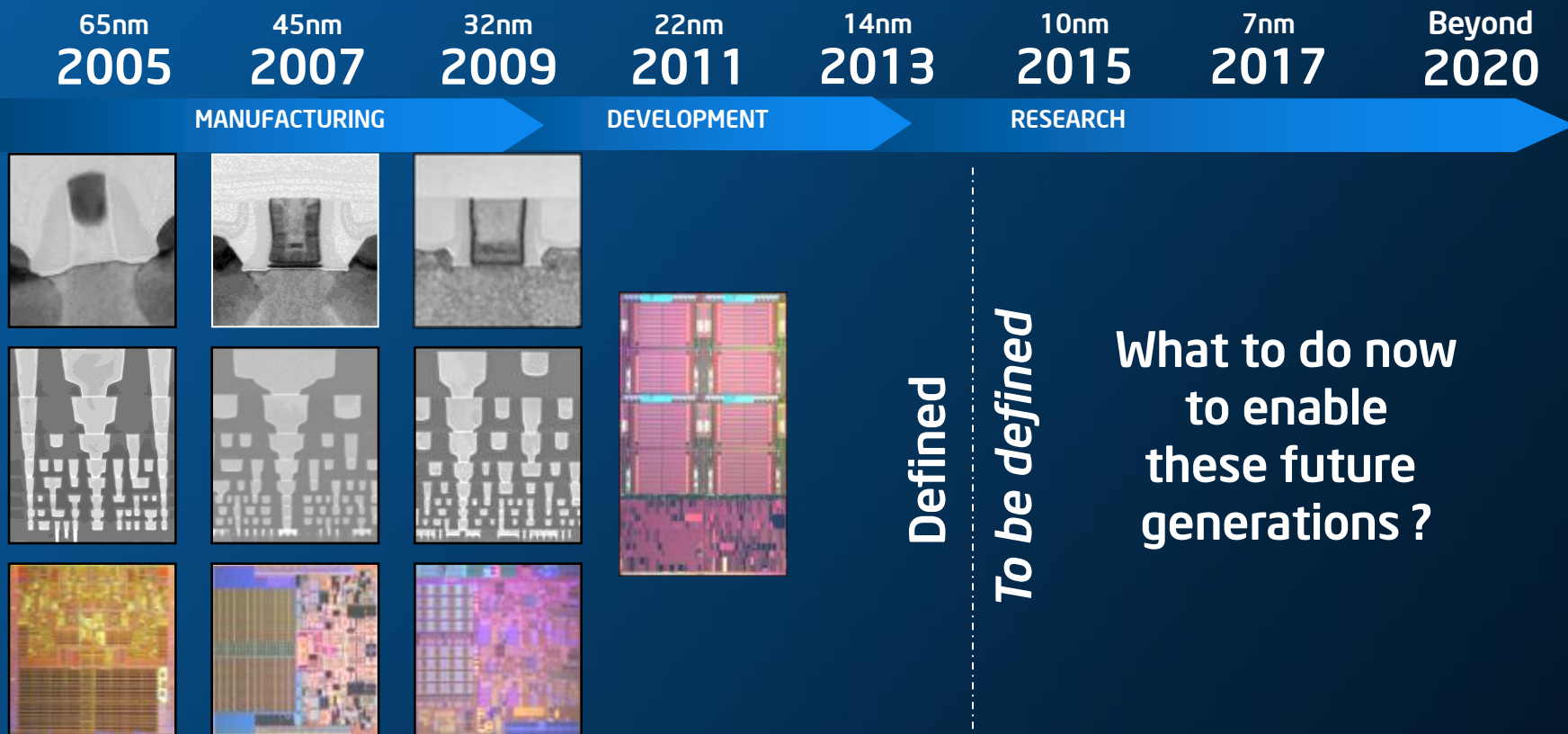
Outline

1. Overview
2. EUV Status and Photoresist Material Challenges
3. Non-traditional scaling materials
 - DSA and others
4. Other Scaling Materials
 - Lines
 - ALD challenges for interconnects
 - And Spaces
 - ILD challenges for dielectrics
5. Summary



CR: Enabling a Steady Technology Cadence

TECHNOLOGY GENERATION

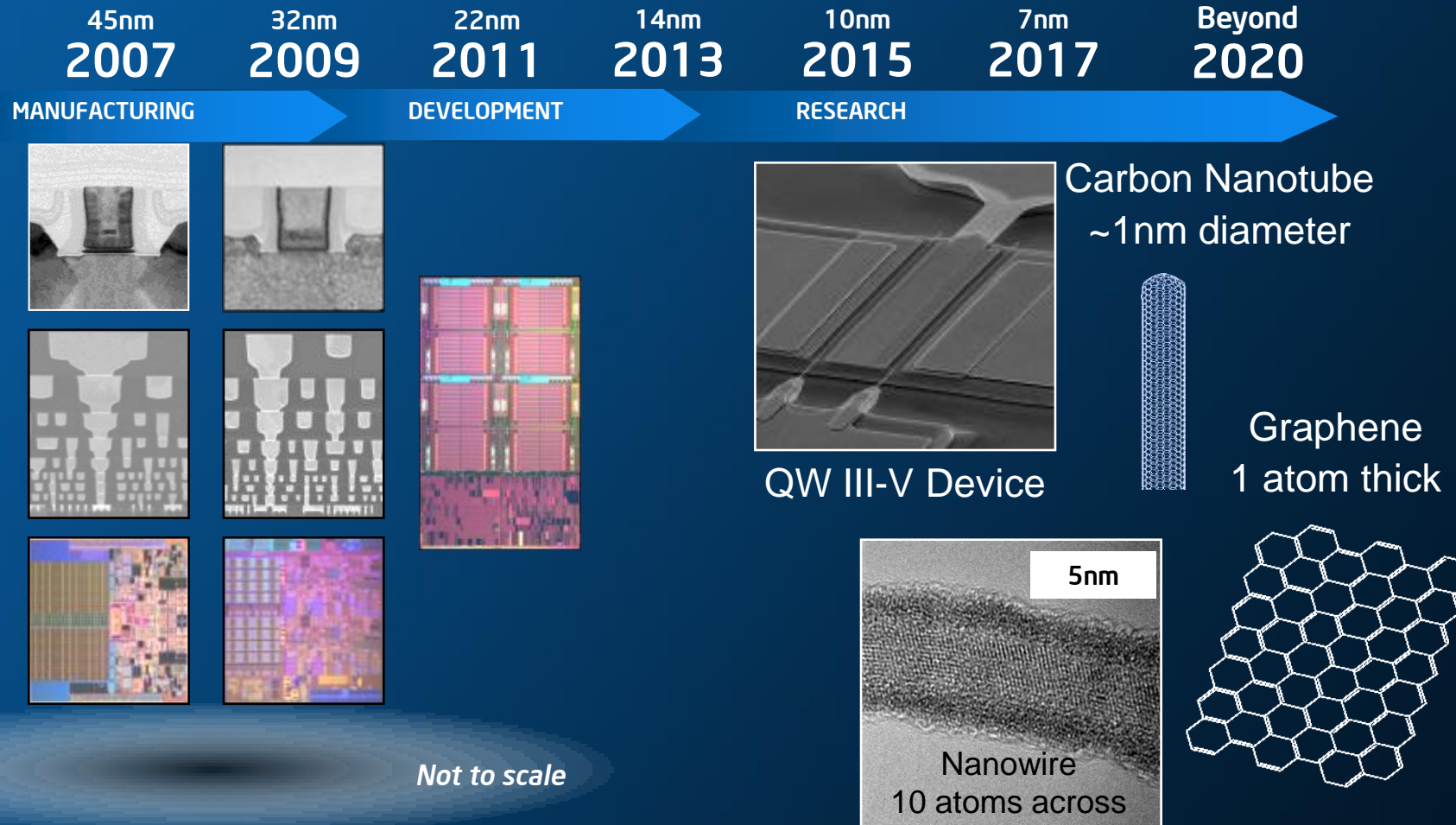


Not to scale



Our visibility always ~10 yrs - need broad exploration

TECHNOLOGY GENERATION



- Silicon lattice is ~ 0.5nm, hard to imagine good devices smaller than 10 lattices across - reached in 2020



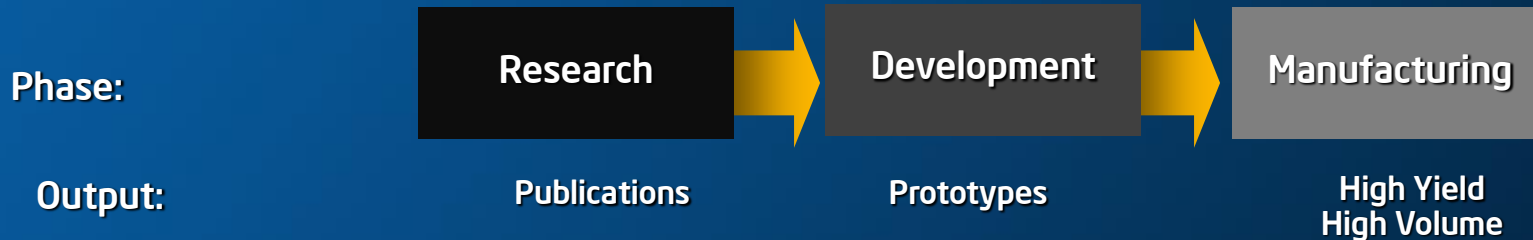
Some Key Areas

- **Material integration**
 - Research to understand & manage below 15nm features
 - **New materials which allow new functions**
 - Managing granularity at small dimensions
- **New function integration**
 - Moving difficult to scale into easier to scale
 - Interfaces and interconnections
 - New functionality to make a platform more valuable
- **Devices as part of a connected network**
- **Discovery beyond our current visibility**
- **Mechanisms to rationalize and mature the portfolio of research investments**



Development and Transfer Model:

Traditional R-D-M Method:



Intel's R-D-M Method:



Collaboration Key to Seamless In-House Research-Development-Manufacturing Pipeline

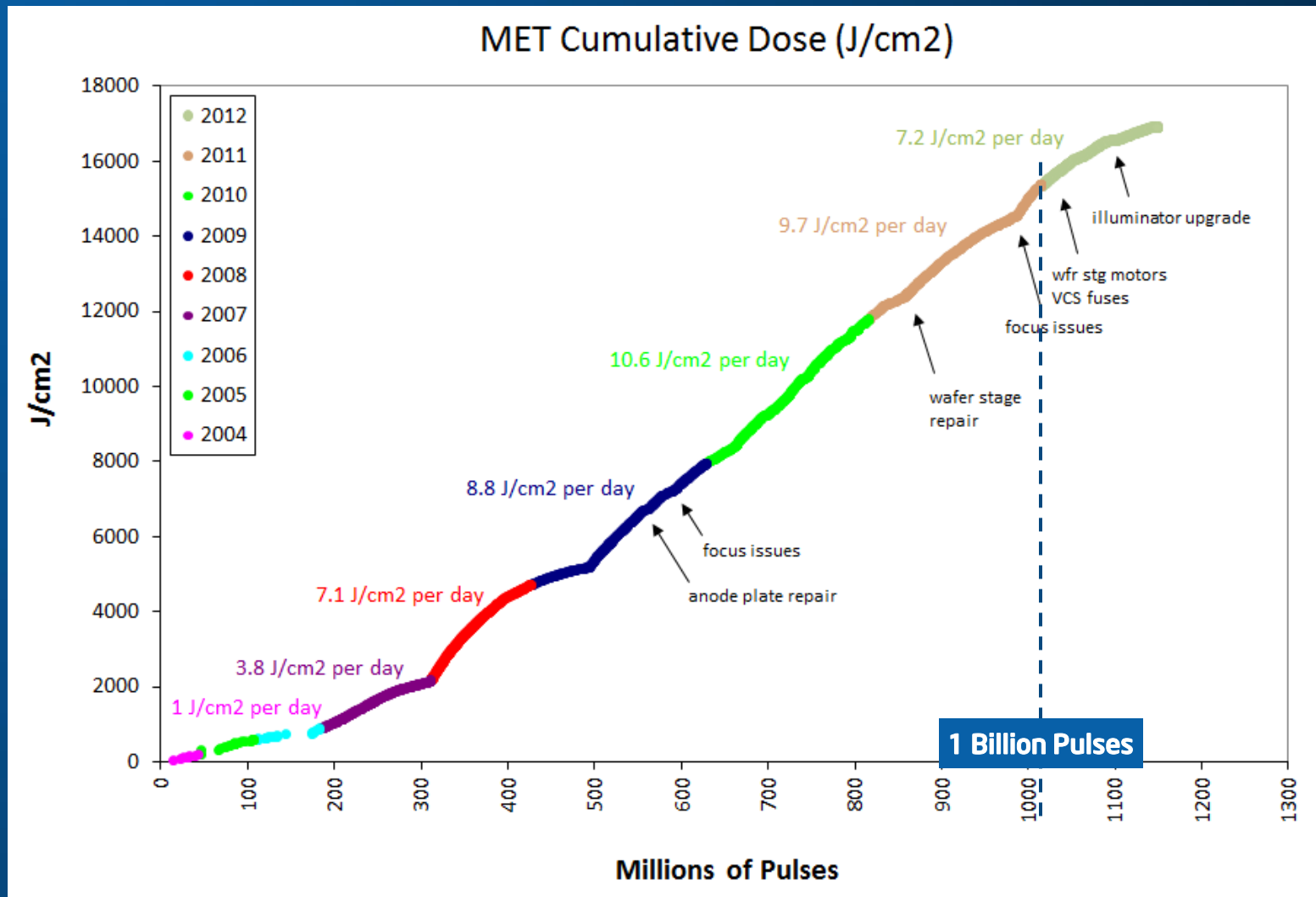


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MET Dose Delivered

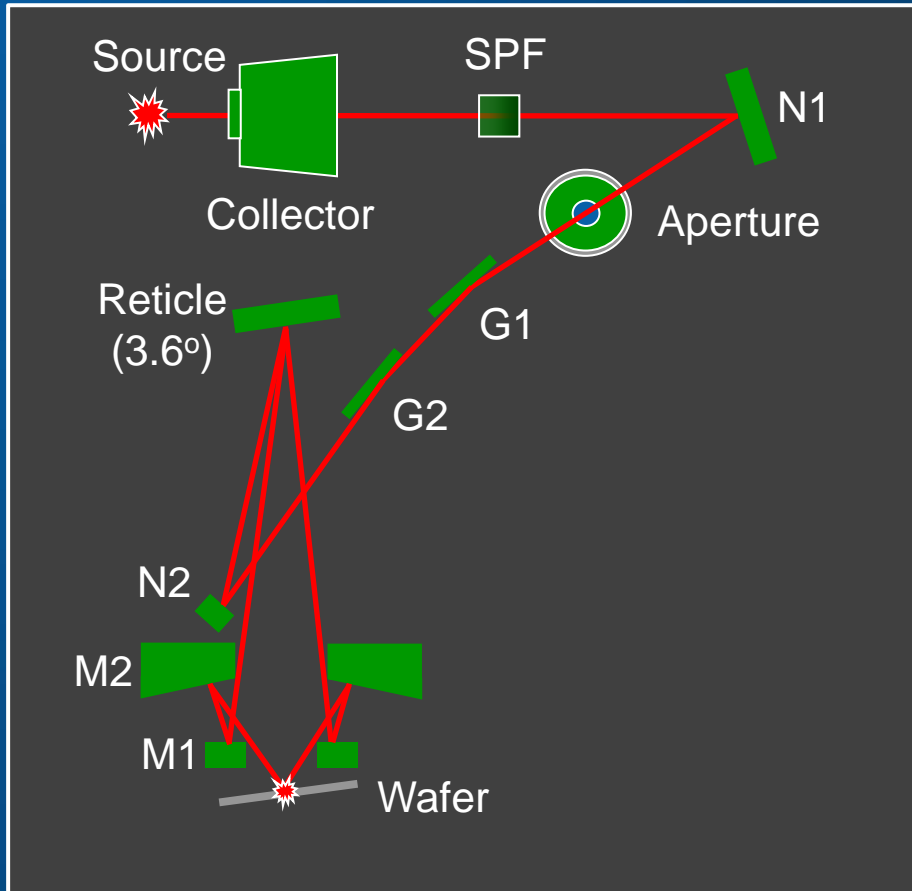


Continued high % MET uptime key to supporting continued rapid materials progress

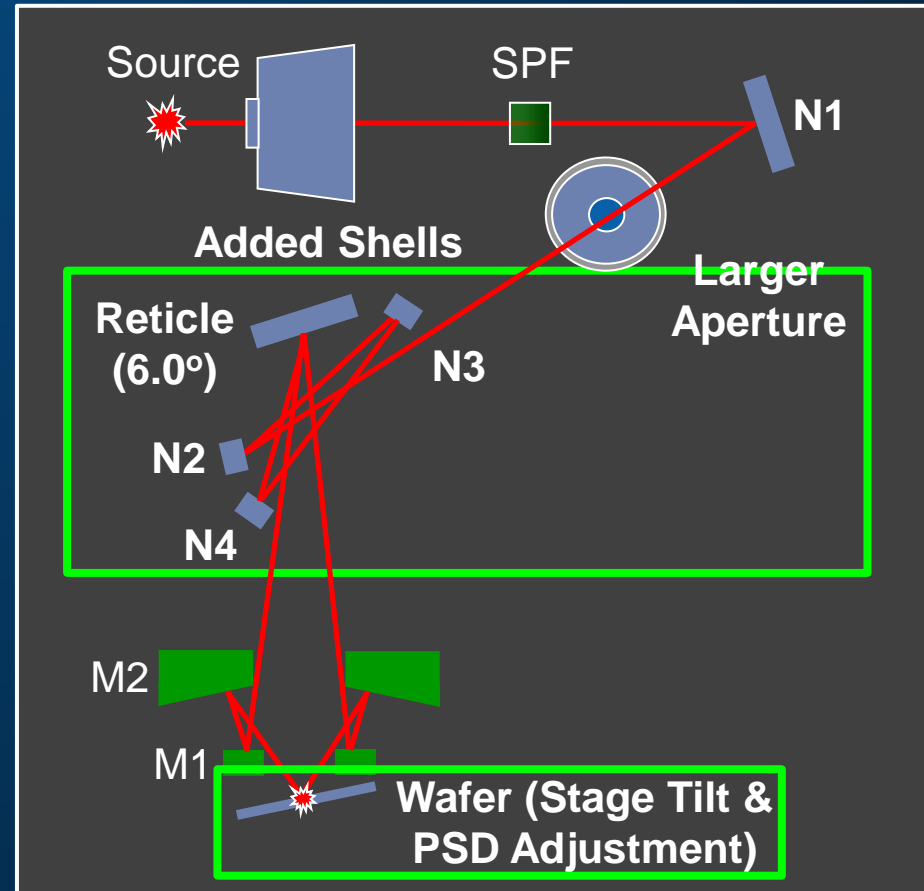


Q2/Q3'12 Illuminator Optics Upgrade

MET Pre-Illuminator Upgrade



MET Post-Illuminator Upgrade

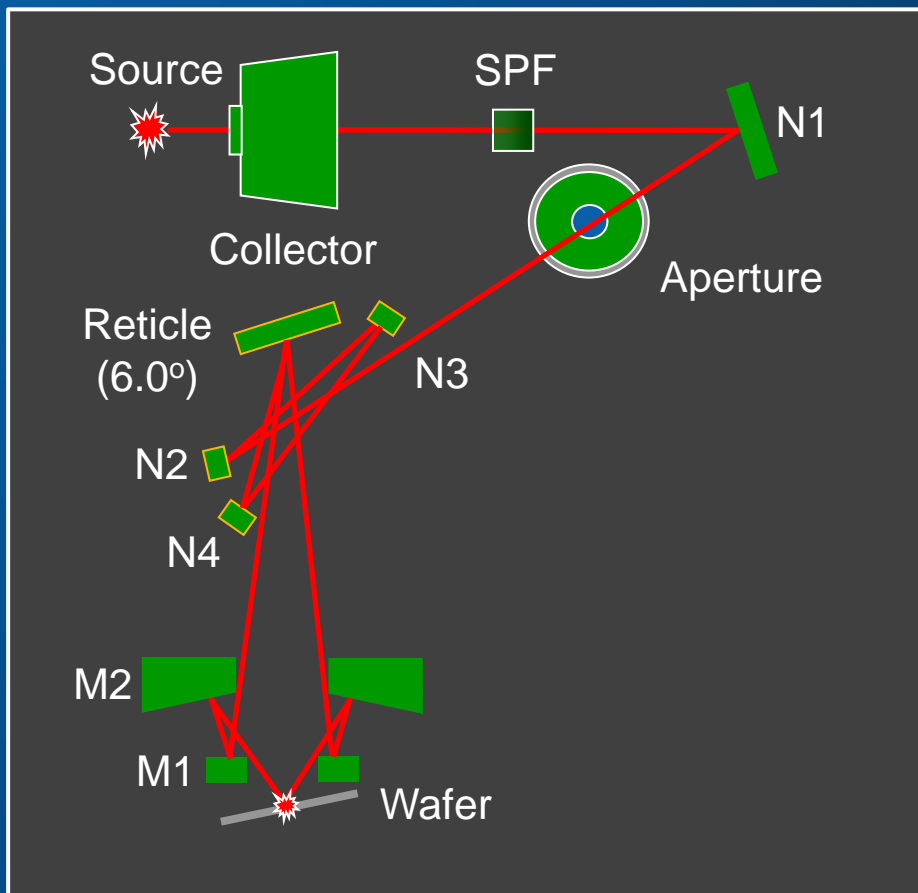


Illuminator Upgrade is Completed supporting 14nm resolution

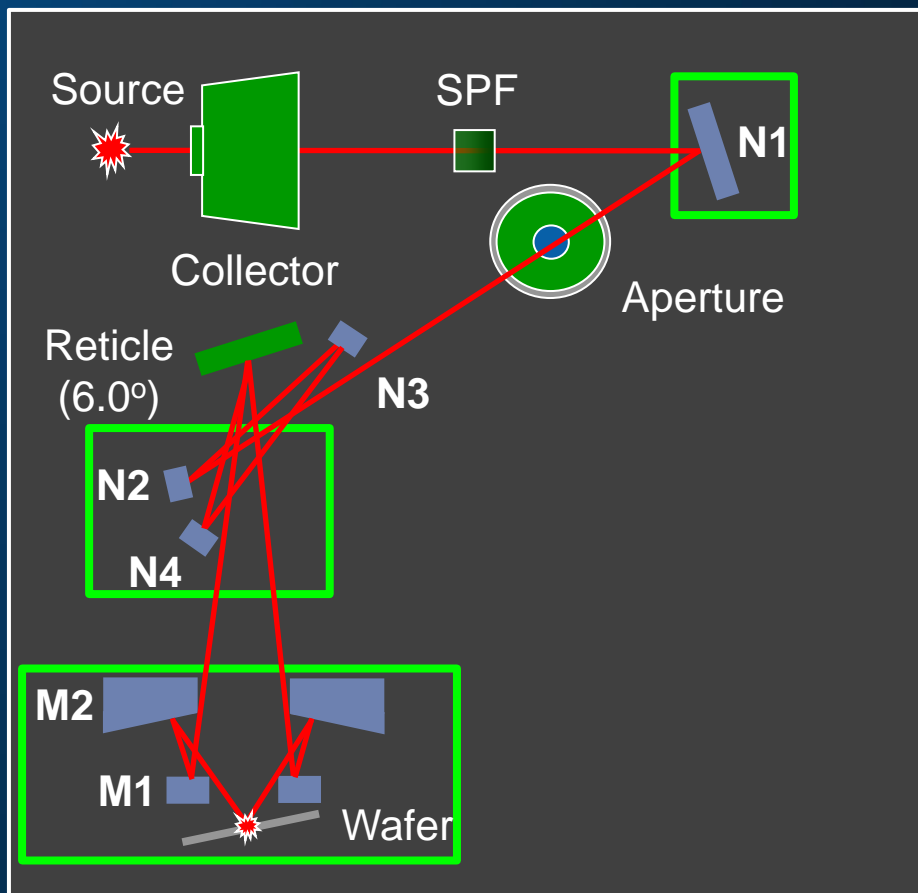


Q4'13 PO & Illuminator Optics Upgrade

2012 MET Post Illuminator Upgrade



Q4'13 MET Post PO + Illuminator Upgrade



PO + Illuminator optics required for 0.5NA (9nm) MET Resolution

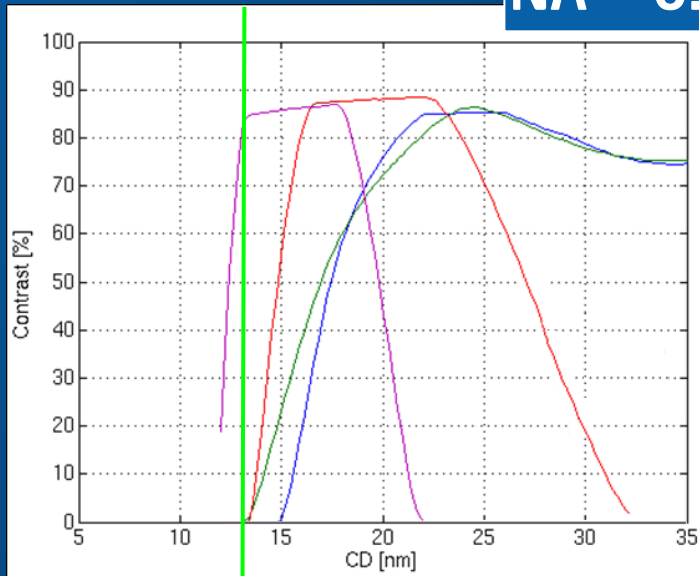
Aerial Image Contrast

Q2 2012 Illuminator Upgrade

- $\sigma = 0.68$, dipole (current)
- $\sigma = 0.90$, dipole (upgrade)
- $\sigma = 0.68$, quadrupole (current)
- $\sigma = 0.90$, quadrupole (upgrade)

$$HP = \lambda / (2 NA \cdot \sigma) / 2$$

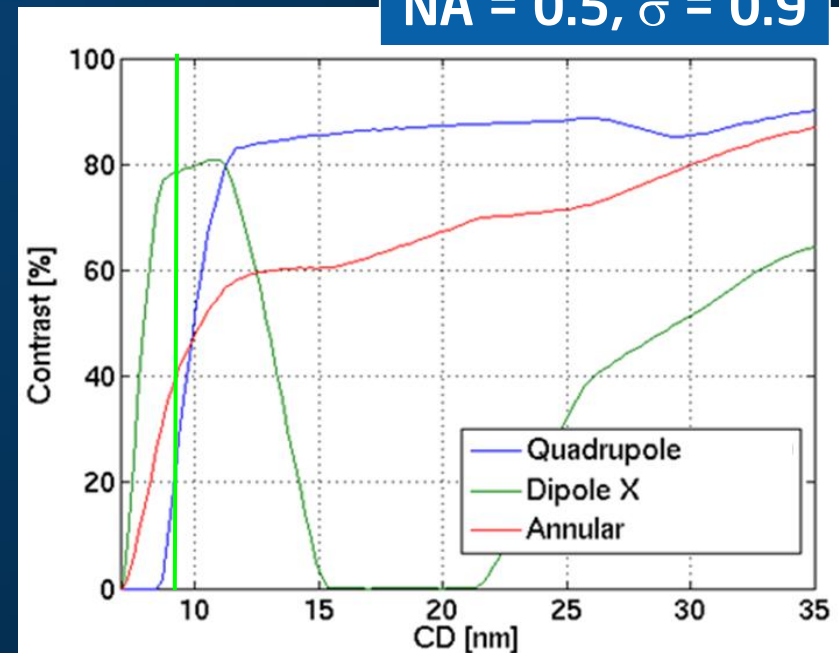
NA = 0.3



1D Resolution improves from
17 nm to ~14 nm HP

Q4 2013 PO & Illuminator Upgrade

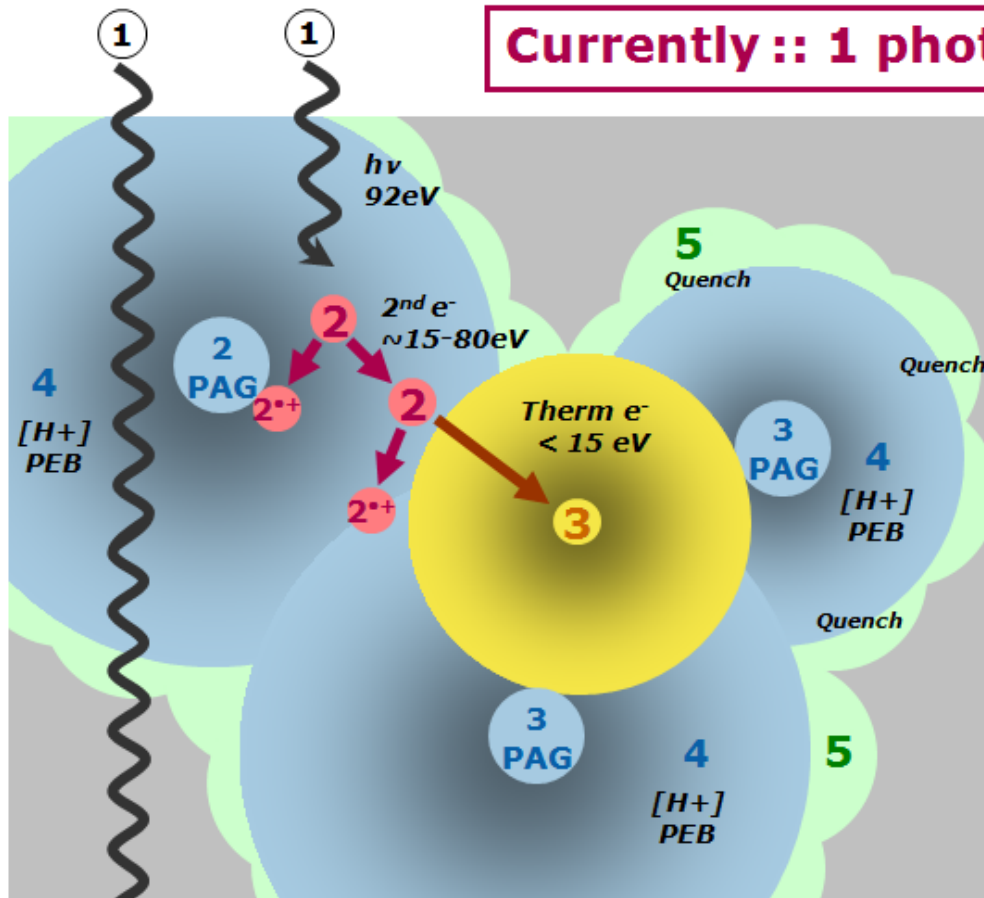
NA = 0.5, $\sigma = 0.9$



1D Resolution improves to 9
nm HP

Mechanism for EUVL Chemically Amplified Resists

Currently :: 1 photon \rightarrow $\sim 4-8$ 2nd e⁻s \rightarrow $\Phi \sim 2-4$



Anisotropic

[1] Photon Absorption

[2] Matrix Ionization

Isotropic

[3] PAG Activation by
Lower Energy
Thermal Electrons

[4] Acid Diffusion /
Quenching

[5] Develop

Substrate

Tagawa, Kozawa, Gallatin, Brainard, Fedynyshyn

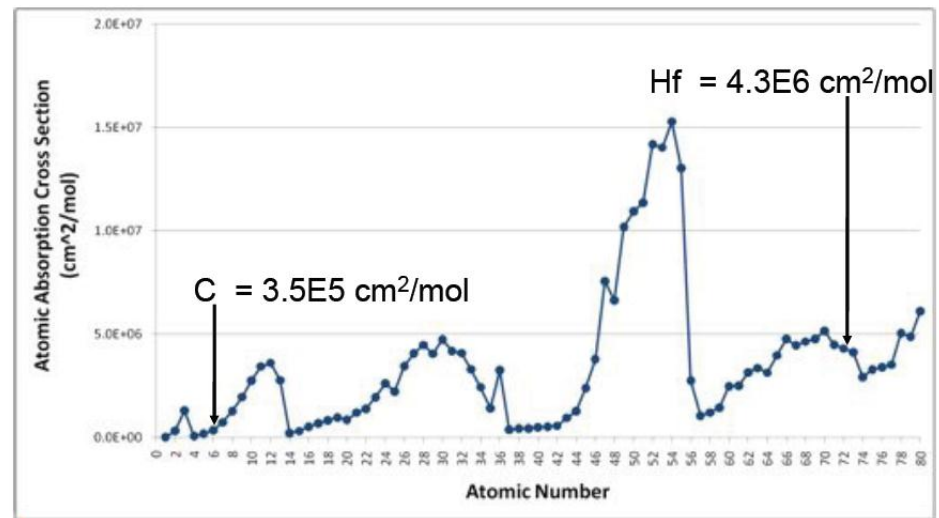
EUV sensitization mechanism unlike that for DUV materials



Periodic Table of the Elements

1 H 1.01	2 He 4.00																		
3 Li 6.94	4 Be 9.01																	10 Ne 20.18	18 Ar 39.95
11 Na 22.99	12 Mg 24.30	13 Al 26.98	14 Si 28.09	15 P 30.97	16 S 32.07	17 Cl 35.45	18 Ar 39.95												36 Kr 83.80
19 K 39.10	20 Ca 40.08	21 Sc 44.96	22 Ti 47.88	23 V 50.94	24 Cr 52.00	25 Mn 54.94	26 Fe 55.85	27 Co 58.93	28 Ni 58.69	29 Cu 63.55	30 Zn 65.39	31 Ga 69.72	32 Ge 72.61	33 As 74.92	34 Se 78.96	35 Br 79.90	36 Kr 83.80		
37 Rb 85.47	38 Sr 87.62	39 Y 88.91	40 Zr 91.22	41 Nb 92.91	42 Mo 95.94	43 Tc (97.91)	44 Ru 101.07	45 Rh 102.91	46 Pd 106.42	47 Ag 107.87	48 Cd 112.41	49 In 114.82	50 Sn 118.71	51 Sb 121.75	52 Te 127.60	53 I 126.90	54 Xe 131.29		
55 Cs 132.91	56 Ba 137.33	57 La 138.91	58 Ce 140.12	59 Pr 140.91	60 Nd 144.24	61 Pm (144.91)	62 Sm 150.36	63 Eu 151.96	64 Gd 157.25	65 Tb 158.93	66 Dy 162.50	67 Ho 164.93	68 Er 167.26	69 Tm 168.93	70 Yb 173.05	71 Lu 174.97	72 Hf 178.49	73 Ta 180.95	74 W 183.85
87 Fr (223.02)	88 Ra (226.03)	89 Ac (227.03)	90 Th (232.04)	91 Pa (231.04)	92 U (238.03)	93 Np (237.05)	94 Pu (244.06)	95 Am (243.06)	96 Cm (247.07)	97 Bk (247.07)	98 Cf (251.08)	99 Es (252.08)	100 Fm (257.10)	101 Md (258.10)	102 No (259.10)	103 Lr (262.10)	104 Rf (261.11)	105 Db (262.11)	106 Sg (263.12)

EUV Photoabsorption Cross Section



Traditional DUV materials (C, H, Si) quite transparent in EUV

Materials Roadmap

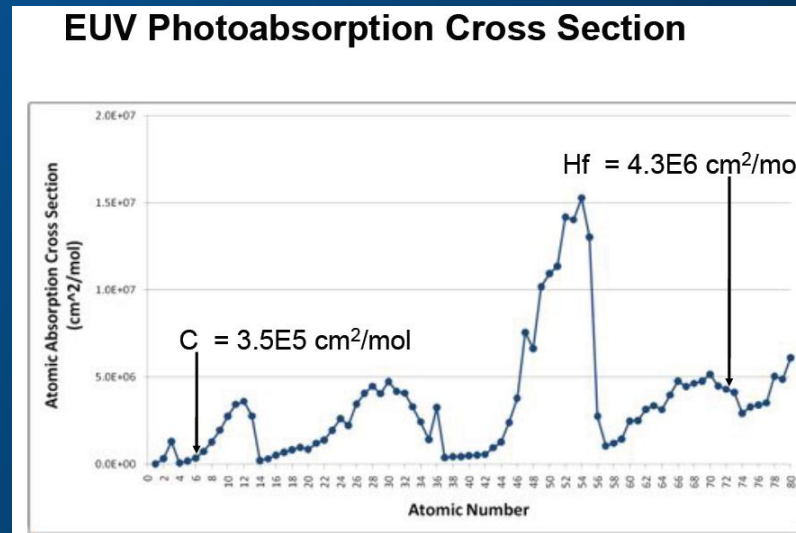
- **Resist**
 - Competing Options
 - Chemically Amplified (CA) Polymeric Resist
 - Diffusion is a challenge :: Esize trends UP
 - Non-CA Inorganic/Semi-Inorganic Resist
- **Developer: Aqueous, Solvent(s), Alcohols/Blends**
 - Patterning can be + or - tone depending on resist
- **Under Layer**
 - Emphasis on multi-layer / tri-layer materials
 - Inorganic resists might serve as direct patternable HM's?
- **DSA**
 - Extensions from 193nm or new concepts applicable to EUV
- **Top Coat**
 - Improve Esize; Reduce LWR; Abate Outassing or OOB impacts to patterning?

All material options are on the table / under evaluation; Esize improvements needed



Considerations / Trends

- **Photospeed:** Non-CA materials must have high EUV OD
 - CA resists have low EUV absorption x-section unless highly fluorinated
 - Metal redox potential + ligand choice will also modulate photo speed



- **LWR:** Reduction of low to mid spatial frequency LWR at resist level will remain challenging
 - DSA might be employed for LWR healing & CDU improvements
 - Non CA resists will likely have a different frequency response

LWR remains a top challenge; Increased photon absorbance
one option for improved pattern efficiency

Considerations / Trends, Contd.

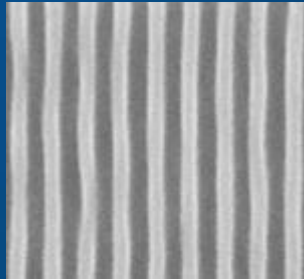
-ve tone holes: improved shot noise statistics, may lower required dose



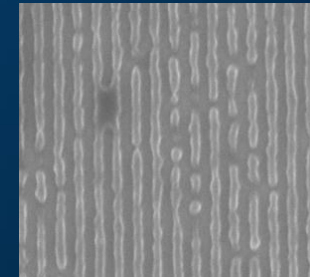
- If $L_D = 5\text{nm}$, $CD=20$, then -ve tone bucket area is $(30/20)^2 = 2.3\times$.
- Shot noise fluctuations scale with #photons.
- So dose could decrease by this factor and give same shot noise statistics
- Tradeoff: pitch limitations (close holes will bridge), rounded corners

Supportive Collaborative Research

- Brainard (UA):
 - Chemically comprehensive semi/inorganic resist project
 - Results are showing promise; mechanism needs further evaluation



30nm HP
Esize ~ 100mj
Dev = 66% IPA/H2O



30nm HP
Esize ~ 1mj
Dev = 17% Acetone/PGMEA

- Non-CAR, CA extensions as well as Chain scission resists are also areas of research focus

Goal: Proof of Concept Demonstration; Rapid Proliferation to Supplier Base

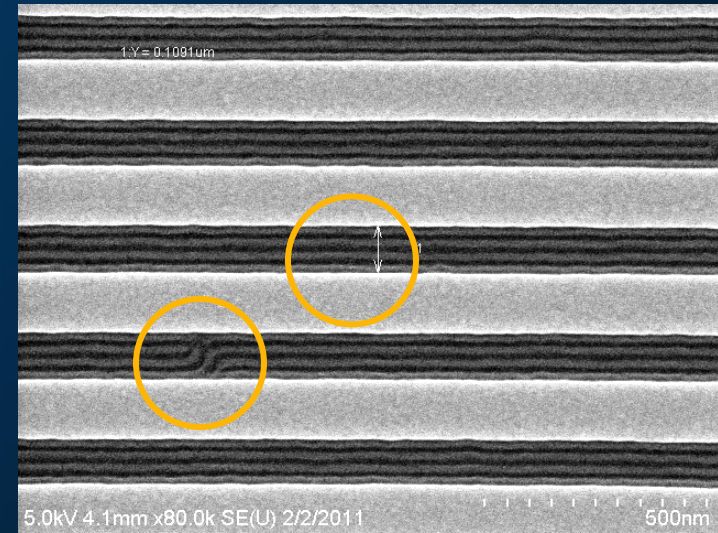
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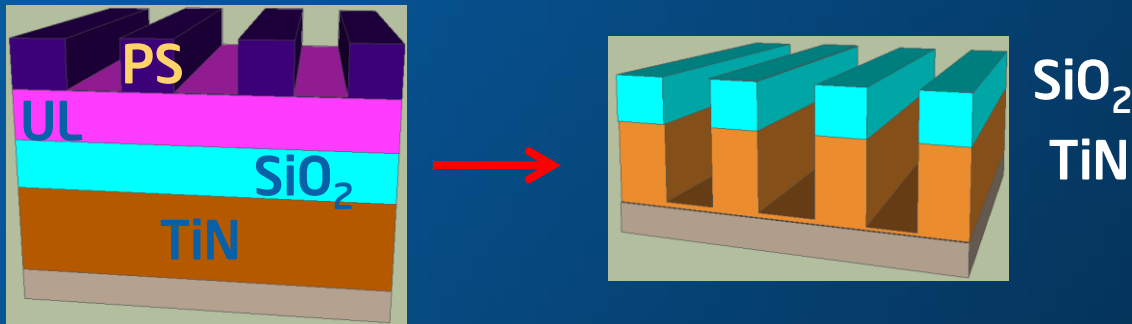


Directed Self Assembly

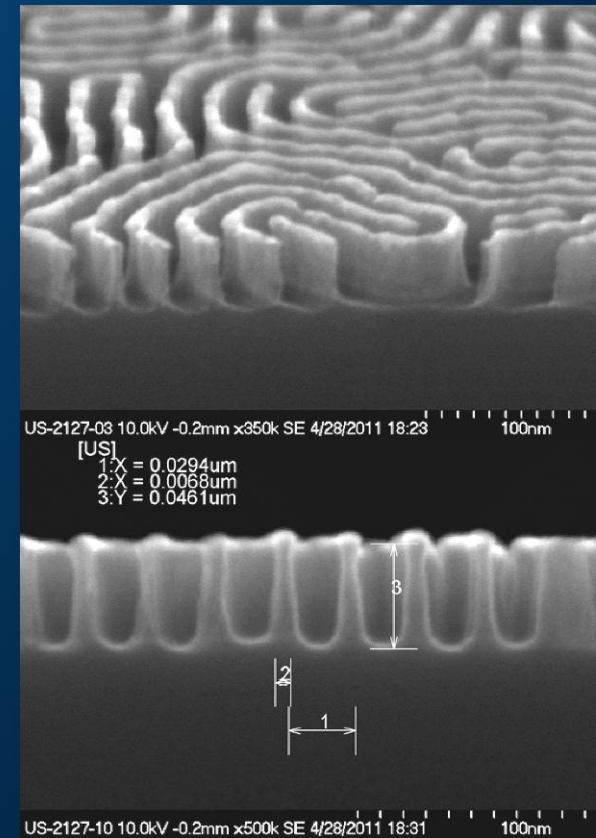
- *Potential* for a low-cost solution for part of the patterning process.
- *How tight?* We need sub-20nm pitch with scalability below that.
- *Process Window:* For a solution to be manufacturable, nearly all variables must allow usable latitude.
 - Guiding Pattern: CD, LER, local surface chemistry. Exception: pitch is very well controlled (defined by mask, litho tool).
 - BCP: thickness, anneal, local molecular wt. and PDI, etc.
- **Defects.** Eventually need $<0.01/\text{cm}^2$.
 - Gross assembly defects (dislocations, disinclinations, etc).
 - Particles, esp. if lift-off process.
 - But also bridges, local overlay failures, buried defects, LER excursions etc.
 - Should be evaluated after etch transfer.



DSA: Etch transfer

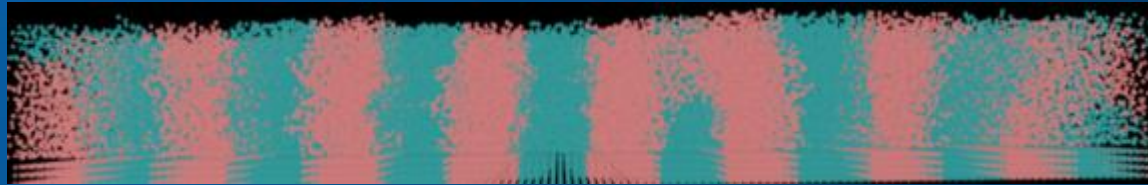


- PS-b-PMMA allows for etch transfer to common underlayers and hard masks
- HM will determine the final pattern. This is ultimately the layer to be inspected for defects.



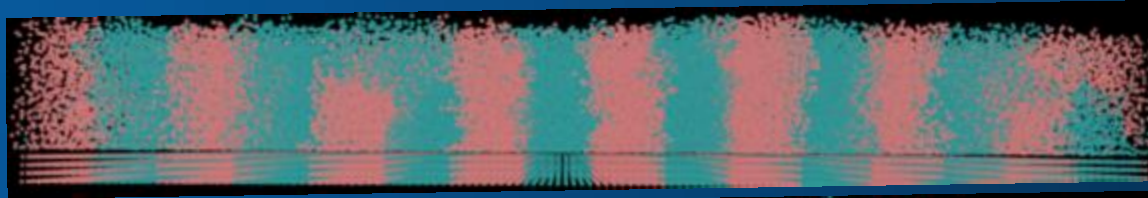
- HM Loss
- TiN:HM sel - ~2:1
- Ar, Cl₂

Probing DSA Patterning Quality vs. χN

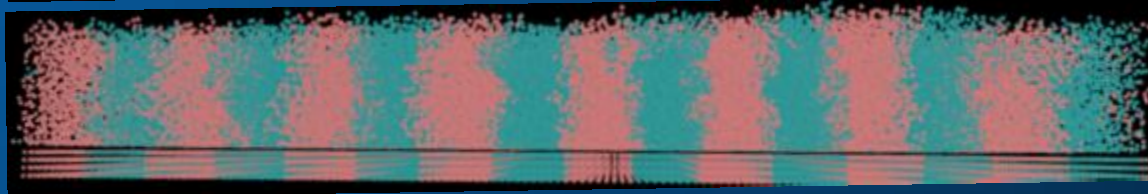


$\chi N=20.2$

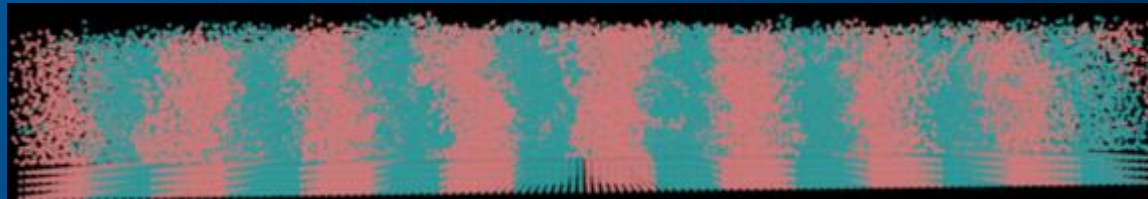
Cross-
Sections
A - red
B - blue



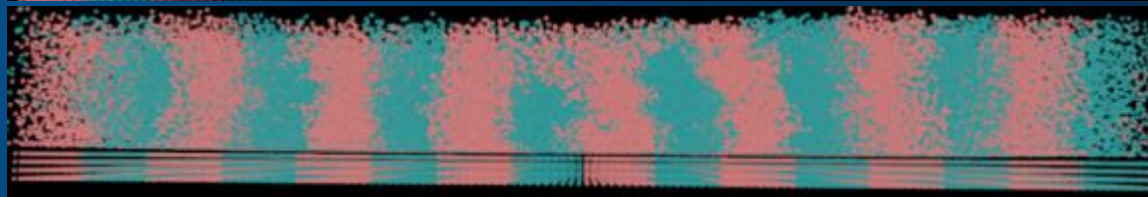
$\chi N=18$



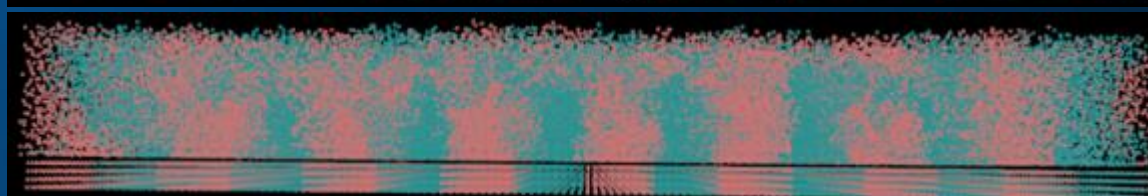
$\chi N=14$



$\chi N=13$
PS-PMMA
20nm pitch



$\chi N=11.5$

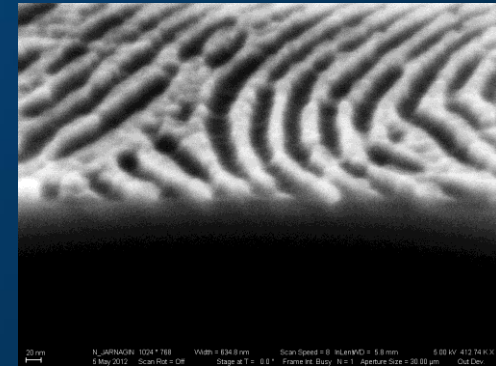


$\chi N=10.5$

PS-b-PMMA may not provide sufficient thermodynamic driving force to achieve extendable dimensions

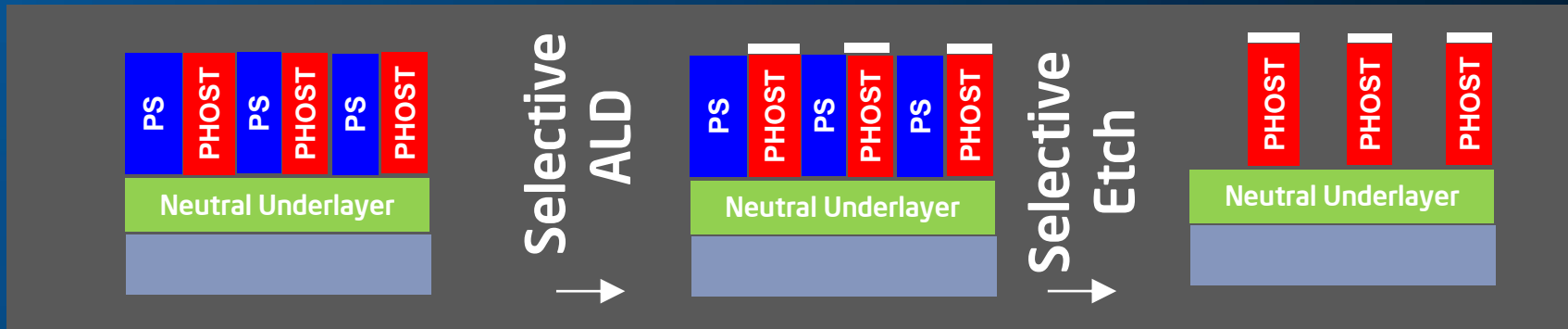
Selective Block Removal of High χ Material: PS-b-PHOST

- **Problem**
 - PS-b-PHOST has low etch contrast
- **Potential Solution**
 - **Selective ALD + Etch**
 - Selective ALD process to -OH functionality
 - Generates high etch resistance between oxide and unreacted PS
- **Key Result**
 - Post etch SEM with PS removed



Selective ALD/Etch
of PS-b-PHOST

Georgia Tech: Henderson et. Al.



Use of high- χ materials may require integrated solutions

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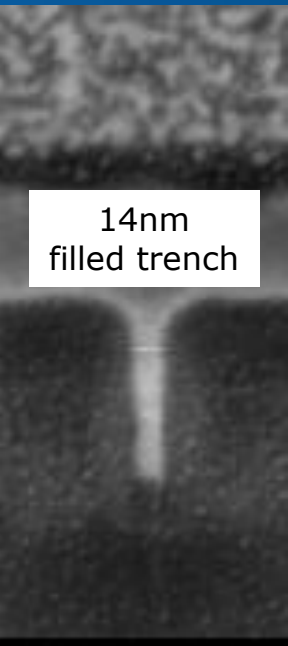
Improved ALD processes needed for new metals and compatible processes

Process criteria:

- Low temperature favored; $< 150\text{ }^{\circ}\text{C}$
- Thermal deposition favored over PEALD
- Substrate compatibility is a challenge

Film criteria:

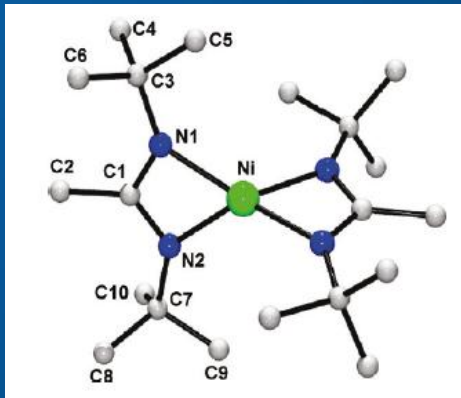
- High purity
- Physically & electrically continuous $< 3\text{ nm}$
 - Selective ALD advantageous



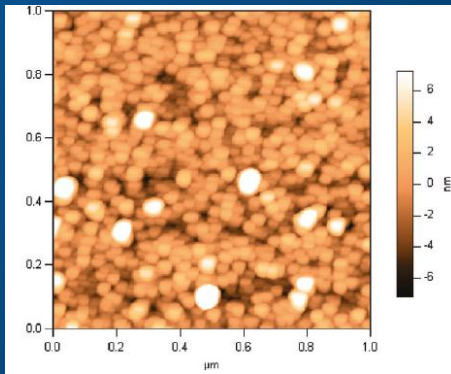
There is a need for new "gentle" metal ALD chemistries based on new mechanisms

New Metal ALD Precursors & Coreactants Needed

Ni AMD



$\text{NH}_3\&\text{H}_2$
CVD : 160-
200°C



- New ligand scaffolds + tailored coreactants needed especially for electropositive metals: Al & Ti.
- Active engagement key to align roadmaps.

R.G. Gordon et al., *Chem. Mater.* 2010

NiN_x film

Computational Chemistry to Accelerate Materials Development

Molecular Properties:
Structure, volatility & thermal stability

Surface reactions

Film/bulk level properties

How can modeling be best used in
materials R&D?

Increasing Complexity

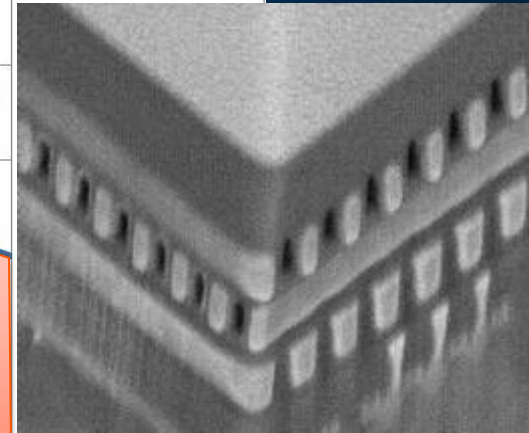
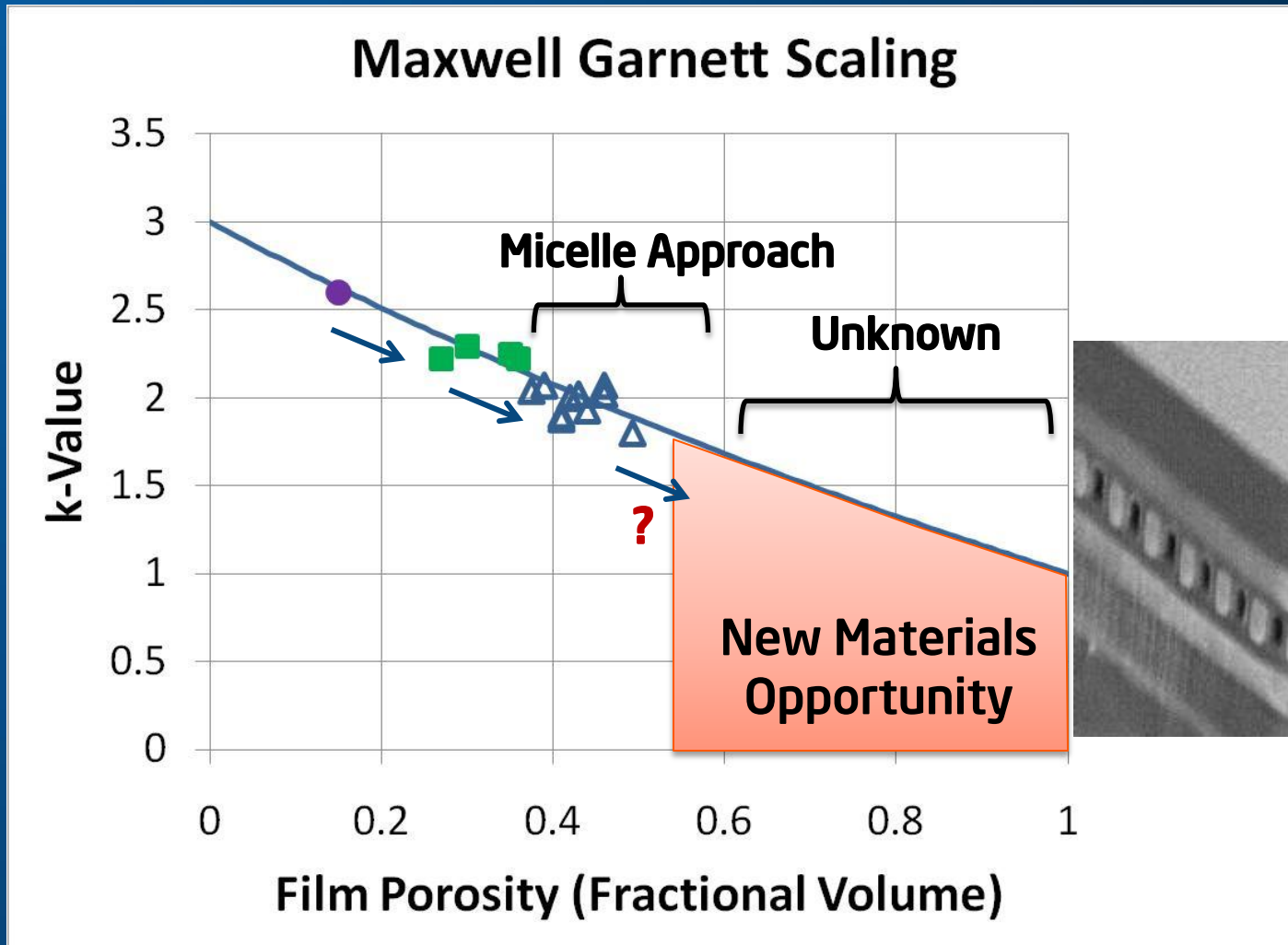


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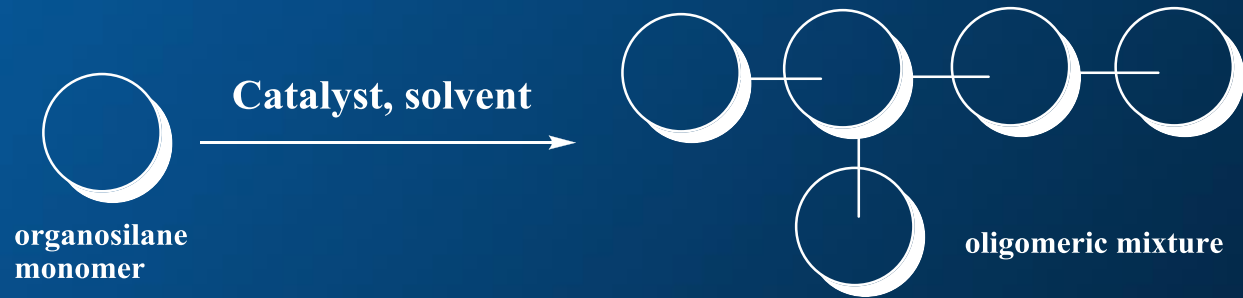


Next Generation low K Materials



- random pore materials collapse beyond ~0.55 fractional volume
- ordered pore structured materials will be required

General Overview of Low K Film Formation



Currently, backbone ILD material is synthesized, mixed with porogen (host-guest) and then coated on wafer and baked to generate thin films of desired porosity.

Future advances will need to couple backbone and porogenic materials to support higher porosities (lower k values).

Would combinatorial approaches be appropriate here?

Organic Porogen and Solvent

Coating
Formulation

Spincoat and Bake

Porous Thin Film

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Overall Summary

- For EUV materials, efforts at fundamental material improvements as well as novel EUV platforms must be redoubled
- Intel will continue to support EUV material evaluation and keep the MET capability relevant through hardware upgrades
- Existing collaborations have yielded promising results around resist materials
- Intel intends to continue expanding our material's collaborations into new areas, including directed self assembly, ALD metal precursors, ILD precursors, etc.
- Looking forward to discussions around new materials collaborations



Thank you

